Effects of Thirty Years of Irrigation on the Genesis and Morphology of Two Semiarid Soils in Kansas

D. Ricks Presley, M. D. Ransom,* G. J. Kluitenberg, and P. R. Finnell

ABSTRACT

Widespread adoption of irrigation began to occur in western Kansas in the 1950s. The western third of the state is in the ustic moisture regime, receiving about 400 to 500 mm of precipitation per year. Irrigation adds an additional 300 to 600 mm of water per year and effectively alters the natural climate. The Richfield and Keith soil series were investigated to determine if irrigation has caused changes in soil properties and morphology, affecting the genesis of irrigated soils. For each series, 10 long-term (28–31 yr) irrigated pedons and 10 adjacent pedons that had never been irrigated were sampled. The pH of the surface horizons of the irrigated Keith and Richfield pedons was 1.0 pH unit higher than the dryland pedons. Exchangeable sodium percentage (ESP) was also higher in irrigated pedons. Irrigation did not significantly affect organic C content or the calcium carbonate equivalent (CCE). Irrigated pedons contained significantly higher amounts of total clay and showed an altered clay distribution within the profile. They also exhibited more strongly expressed argillic horizon properties in the field and in thin section than nonirrigated pedons. The data indicate that ≈30 yr of irrigation increased clay illuviation and mineral weathering, altered the surface horizon pH and ESP, and modified the natural genetic processes by increasing the rate of pedogenic activity.

Richfield (fine, smectitic, mesic Aridic Argiustolls) and Keith (fine-silty, mixed, superactive, mesic Aridic Argiustolls) are two of the most extensive soil series in western Kansas. Combined, they cover over two million hectares, nearly 350 000 of which are irrigated. These semiarid soils are extremely important for agriculture and are considered to be two to three times more productive when irrigated. In western Kansas, irrigation from surface water bodies began as the area was settled by Europeans in the 1800s. Irrigated agriculture greatly expanded in the mid-1900s using water from the High Plains Aquifer, a high-quality water source that is low in dissolved salts (Buchanan and Buddemeier, 2001).

The Richfield and Keith soils formed in Peoria loess under short- and mid-grass prairie vegetation. Relief varies from nearly level to gently rolling. Soil profile development in Kansas decreases from east to west in response to a precipitation gradient (Gunal, 2001). The western third of the state is in the ustic moisture regime, receiving approximately 375 to 600 mm of precipitation per year. Average irrigation practice adds 300 to 600 mm of water per growing season.

In effect, irrigation alters the natural climate factor of soil formation. The main soil morphological and mineralogical properties that correlate with climate are organic matter content, clay content, kind of clay and iron minerals, color, various chemical extracts, and the presence or absence of calcium carbonate and other soluble salts (Birkeland, 1999). Altering the climate has been shown to have various effects on soil properties and processes, such as changing the amount of biomass produced and the chemical and physical properties of soil.

Perhaps one of the most researched aspects of irrigation is the effect on soil chemical properties. Reported changes resulting from irrigation vary greatly and are largely dependent on the quality of the irrigation water. Much research was performed in western Kansas in the 1950s and 1960s concerning the effect of irrigation on the chemical properties of soils (Dixon, 1960; Lynn, 1958; Naddih, 1960). Accumulations of soluble salts, exchangeable sodium, and calcium carbonate, as well as increases in electrical conductivity (EC) and pH, occurred in soils of southwest Kansas that were irrigated with saline surface waters. Soil texture was considered to affect infiltration rate and thus the rate of accumulation of soluble salts, calcium carbonates, etc., but the effect of the changes in chemical properties on soil morphology in western Kansas was not studied in these investigations.

Similar studies have been conducted around the world. Hussein et al. (1992) investigated why crop yields did not increase with the introduction of better crop varieties in Zimbabwe. They compared irrigated, nonirrigated, and noncultivated fine-textured soils and discovered accumulations of salts and phosphorous in the irrigated soils, finding no differences in pH, C, or N with irrigation. In contrast, other studies have reported an increase in total carbon (TC) and soil organic carbon (SOC) with irrigation. Bordovsky et al. (1999) found that irrigation led to a significant increase in organic matter content in some sandy, semiarid soils in Texas. Lueking and Schepers (1985) studied the effects of irrigation development on total soil C and N, N availability of the Sandhills soils in Nebraska, and also reported increased TC with irrigation vs. the native dry rangeland. Researching the fine-textured soils at Konza Prairie near Manhattan, KS, Williams (2001) found that irrigation increased SOC levels on dry, upland positions but did not significantly affect SOC levels on wetter, lowland positions. Although the conclusions of these studies vary with respect to the effect of irrigation on

D. Ricks Presley, M.D. Ransom, and G.J. Kluitenberg, Dep. of Agronomy, Kansas State Univ., Manhattan, KS 66506; P.R. Finnell, USDA-NRCS, Lincoln, Nebraska. Contribution no. 04-224-J from the Kansas Agric. Exp. Stn., Manhattan, KS. Received 6 Jan. 2004. *Corresponding author (mdransom@ksu.edu).

Published in Soil Sci. Soc. Am. J. 68:1916–1926 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CCE, calcium carbonate equivalent; COLE, coefficient of linear extensibility; EC, electrical conductivity; ESP, exchangeable sodium percentage; FC:TC, ratio of fine clay to total clay; SAR, sodium adsorption ratio; SOC, soil organic carbon; TC, total carbon.

TC and/or SOC (depending on the soil texture), all concluded that irrigation caused no changes in physical properties such as texture, bulk density, aggregate stability, or hydraulic conductivity.

The effects of long-term (10–230 yr) irrigation of desert soils in Saudi Arabia were studied by Heakal and Al-Awajy (1989) and Khalifa et al. (1989). They found significant increases in calcium carbonate accumulation and clay illuviation in the soil profiles with increasing years of irrigation (Heakal and Al-Awajy, 1989). Khalifa et al. (1989) also studied the micromorphology of these soils, and observed an increase in the separation and concentration of plasma with increasing time under irrigation. Similarly, Mathieu (1978) compared one uncultivated pedon and one pedon that had been irrigated by gravity for 10 yr, finding that with irrigation there was increased compaction, decreased porosity, and an increase in ferriargillans in field observations as well as in thin section. Wierzchos et al. (1997) studied a pair of irrigated (100 yr) and nonirrigated pedons in northeast Spain, reporting changes in pore sizes and distribution with irrigation. The nonirrigated pedon had greater macropore volume and an even pore-size distribution, whereas the irrigated pedon predominately contained very small pores. Therefore, in contrast to the studies previously discussed, these studies did report and conclude that irrigation impacted physical properties.

Currently, it is unclear what impact long-term irrigated farming systems will have on the morphology of soils in western Kansas. Increasing precipitation through irrigation will likely increase the intensity and rate of soil-forming processes and thus, soil formation (Jenny and Leonard, 1933). Of particular interest in the present study is the effect of irrigation on SOC, calcium carbonate, layer silicate translocation, and mineral weathering. Therefore, the objectives of this study were to investigate and quantify what morphological, chemical, and physical differences exist between several irrigated and dryland pedons of two important agricultural soils in western Kansas.

MATERIALS AND METHODS

Ten pedons each of Richfield and Keith soils were investigated at two sites located in Finney and Thomas Counties in western Kansas (Fig. 1). The sites selected for this study were chosen to be representative of the soil series and surrounding area while minimizing the effects of other cultural practices aside from irrigation. The slopes at both sites were 0 to 1%. Neither site has been land leveled or received applications of manure or lime. The sites had been irrigated by center-pivot sprinkler systems for a period of 28 to 31 growing seasons at the time of sampling for the Richfield and Keith soils, respectively. At each site, a single well was used to pump water from the High Plains Aquifer, and the water was distributed in a circle across the 64-ha field by a center pivot sprinkler irrigation system. Corn and soybeans are generally grown under irrigation and wheat and sorghum are grown on dryland fields. For each soil series, five irrigated and five dryland pedons were described and sampled. The irrigated and dryland pedons were located between 70 and 100 m apart and were located within the same map unit delineation. Figure 2 illustrates the sampling method that was used at the Richfield site, and the same scheme was used at the Keith site. At each site, pits

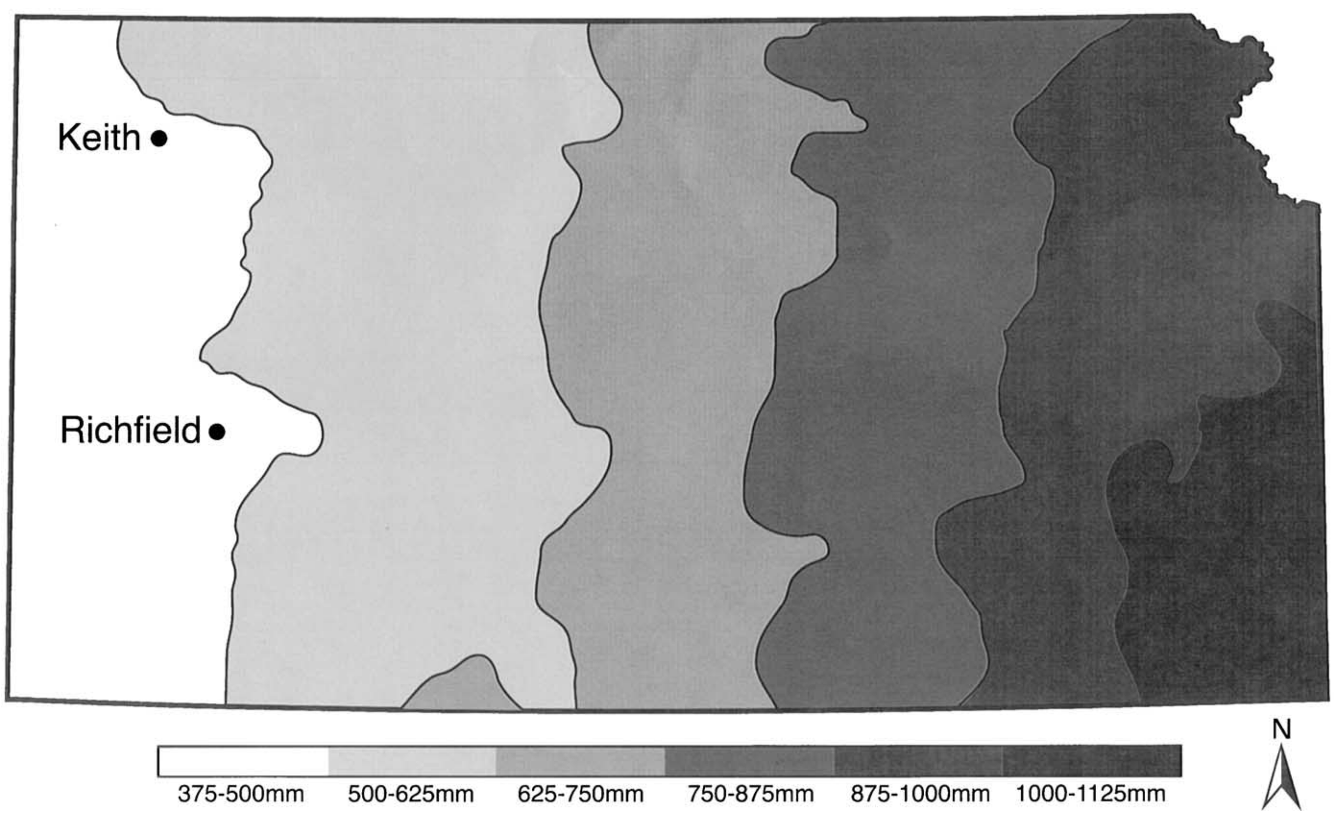

Fig. 1. Site locations and mean annual precipitation for Kansas. Figure modified from Goodin et al. (1995).

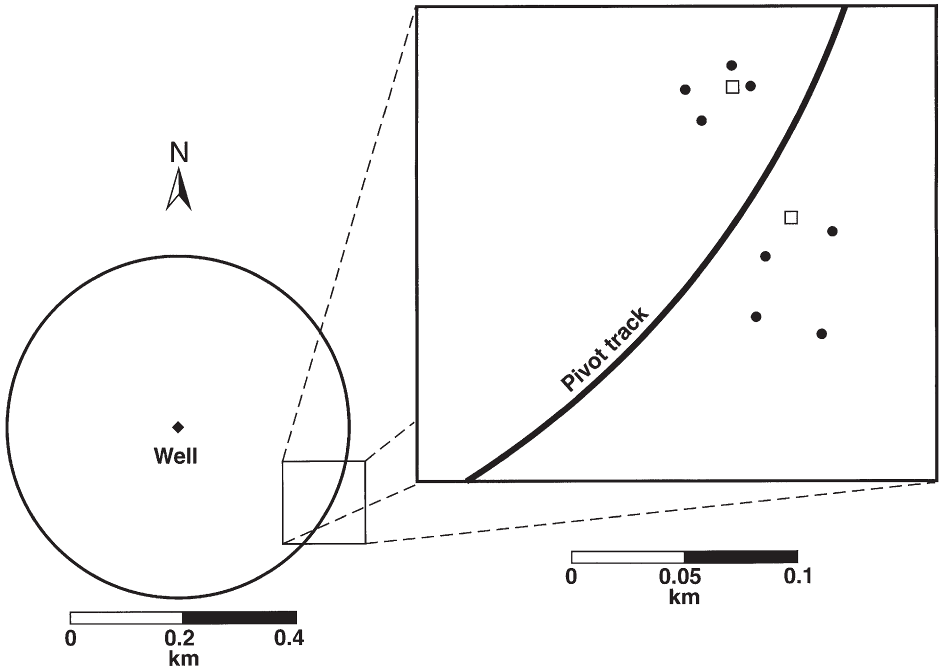

Fig. 2. Sampling scheme used at the Richfield site location. The area inside the circle is irrigated by water pumped from a well located in the center of the field. In the inset diagram, the pivot track delineates the irrigated land from the dryland. The squares indicate pit locations and the circles represent pedons sampled using a Giddings probe.

were dug by a backhoe to a depth of nearly 2 m. Additional pedons were sampled using a truck-mounted Giddings probe.

Soil Property Characterization

Detailed morphological descriptions were made using the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 1998). Bulk samples were collected from each horizon. Thick horizons (>20 cm) were split and subsampled. Air-dry bulk samples were crushed with a wooden rolling pin and passed through a No. 10 sieve with 2-mm square openings. Soil pH was determined in a 1:1 soil-to-water suspension after method 8C1F of the Soil Survey Laboratory Staff (1996). The TC was determined using a high-frequency induction furnace (Leco Model CNS-2000, St. Joseph, MI) following the procedure of Tabatabai and Bremner (1970). Particle size distribution was determined using a modification of the pipet method of Kilmer and Alexander (1949) and method 3A1 from the *Soil Survey Laboratory Methods Manual* (Soil Survey Laboratory Staff, 1996). Organic matter was removed from samples containing >1.4% total C with 30% hydrogen peroxide. The CCE was estimated by the Piper method (Hesse, 1971). Soil organic carbon (SOC) was calculated by adjusting the TC content using the CCE to account for C contained in calcium carbonate. The ESP was determined by the National Soil Survey Laboratory, in Lincoln, NE, following method 5D2 of the Soil Survey Laboratory Staff (1996).

Three clods per horizon were collected for bulk density measurements by method 4A1 of the Soil Survey Laboratory Staff (1996). Three clods per horizon also were collected and trimmed for thin section preparation, marked for direction of orientation, and placed in cardboard boxes with dividers. Thin sections were prepared by a commercial laboratory (Texas Petrographics, Houston, TX) and examined with a petrographic microscope (Model Optiphot-Pol, Nikon, Melville, NY) using plane-polarized, circularly polarized, and crossed-polarized light. They were photographed using a camera system (Model UFX, Nikon, Melville, NY) attached to the microscope. Thin sections were originally described qualitatively using the terminology of Brewer (1976) and were later described using the terminology of Stoops (2003).

Irrigation water samples were collected and analyzed from both wells. The EC was measured using a conductivity meter and probe (Model 441, Corning, Corning, NY). The pH was measured on a dual pH automated analyzer (Model AS3000, Lab Fit, Perth, Australia). Concentration of Ca, Mg, K, and Na present in the water samples was determined with an atomic absorption spectrophotometer (Model 3100, Perkin-Elmer, Wellesley, MA) and the sodium adsorption ratio (SAR) was calculated. Statistical analyses were performed using a *t* test comparison (SAS Institute, 1999).

Analysis of Clay Content and Soil Organic Carbon Distributions

Differences in the clay content and SOC distributions of selected pedons were evaluated by examining (i) the total mass of clay or SOC per unit area between the soil surface and a specified depth, and (ii) the center of mass of the clay or SOC distributed between the soil surface and a specified depth. The total mass of clay or SOC per unit area, M_z (g cm^{-2}), between the soil surface and depth z (cm) is

$$M_z = \int_0^z m(s)ds, \qquad [1]$$

where $m(z)$ is the vertical distribution of clay or SOC mass per unit volume (g cm^{-3}) and s is the variable of integration. Equation [1] can be evaluated by using the alternative form

$$M_{z_n} = m_1(z_1) + m_2(z_2 - z_1) + \ldots + m_n(z_n - z_{n-1}), \qquad [2]$$

where m_1, m_2, ..., m_n are discrete values of clay or SOC mass per unit volume for sampled horizons (or portions of horizons), and z_1, z_2, ..., z_n are discrete depths representing horizon boundaries. For clay content distributions, the values

Table 1. Abbreviated field descriptions and laboratory data for selected Richfield and Keith pedons.

Depth	Horizon	Matrix color†	Clay coatings‡	Sand	Clay	FC:TC§	Textural class	Bulk density¶	pH#	ESP††	SOC‡‡	CCE§§
cm				—— % ——				g cm^{-3}			—— g kg^{-1} ——	
				Dryland Richfield pedon S00KS055011								
0–13	Ap1	10YR 3/2		9.2	30.4	0.31	sicl	1.34	6.7	1	16.6	11
13–21	Ap2	10YR 3/2		9.4	27.2	0.25	sil/sicl	1.53	7.7	1	8.5	18
21–38	Bt1	10YR 3/2	D F A 10YR 2/2	9.4	30.7	0.41	sicl	1.50	7.6	1	7.1	13
38–57	Bt2	10YR 3/3	D F A 10YR 3/3	9.2	36.4	0.51	sicl	1.60	7.6	1	4.2	17
57–83	Btk1	10YR 4/3	P F V 10YR 4/3	7.2	33.9	0.39	sicl	1.62	8.0	1	3.0	59
83–114	Btk2	10YR 5/4	P F V 10YR 4/3	6.8	26.9	0.16	sil	1.38	8.1	1	2.7	121
114–163	Bk1	10YR 5/4		7.7	22.8	0.11	sil	1.28	8.2	1	2.1	96
163–200	Bk2	10YR 5/4		9.0	23.9	0.11	sil	1.36	8.2	2	1.7	77
				Irrigated Richfield pedon S00KS055016								
0–12	Ap1	10YR 3/2		10.4	25.0	0.23	sil	1.26	7.5	3	15.8	10
12–23	Ap2	10YR 3/2		9.2	31.2	0.39	sicl	1.45	7.2	2	8.0	21
23–35	Bt1	10YR 3/2	C F A 10YR 2/2	8.8	37.0	0.52	sicl	1.58	7.6	1	5.1	21
35–53	Bt2	10YR 3/2	C F A 10YR 2/2	8.5	40.4	0.57	sic	1.81	7.8	2	4.1	22
53–72	Btk1	10YR 5/3	C F A 10YR 3/2	7.1	40.9	0.47	sic	1.70	8.0	3	2.7	48
72–99	Btk2	10YR 6/3	P F V 10YR 4/3	6.8	30.2	0.17	sicl	1.46	8.2	5	1.0	154
99–122	Btk3	10YR 6/4	P F V 10YR 4/4	7.4	22.5	0.12	sil	1.29	8.2	5	2.5	123
122–145	Btk3	10YR 6/4	P F V 10YR 4/4	7.7	20.7	0.11	sil	1.29	8.1	6	1.0	102
145–180	Btk4	10YR 6/4	P F V 10YR 4/4	8.0	19.1	0.10	sil	1.23	8.0	8	1.9	86
				Dryland Keith pedon S00KS193001								
0–11	Ap1	10YR 3/2		14.0	19.0	0.41	sil	1.37	6.0	2	13.5	15
11–27	Ap2	10YR 3/2		12.9	25.3	0.46	sil	1.48	6.6	1	8.6	22
27–43	Bw	10YR 3/3		12.1	24.5	0.42	sil	1.32	7.3	1	6.4	18
43–59	Btk1	10YR 4/3	D F V 10YR 3/2	13.4	23.2	0.27	sil	1.34	8.0	1	3.8	47
59–71	Btk2	10YR 5/3	D F V 10YR 3/2	12.8	23.1	0.25	sil	1.40	8.1	1	2.6	91
71–104	Btk2	10YR 5/3	D F V 10YR 3/2	13.0	19.9	0.21	sil	1.32	8.2	2	2.8	71
104–127	Btk3	10YR 5/4	D F V 10YR 4/3	15.6	19.5	0.16	sil	1.24	8.2	2	1.2	92
127–150	Btk3	10YR 5/4	D F V 10YR 4/3	16.7	17.3	0.16	sil	1.23	8.6	2	0.2	104
150–175	Bk	10YR 6/4		17.1	16.5	0.15	sil	1.23	8.6	2	0.3	92
175–200+	Bk	10YR 6/4		17.3	15.3	0.16	sil	1.23	8.6	3	0.0	86
				Irrigated Keith pedon S00KS193006								
0–10	Ap	10YR 3/2		13.5	19.1	0.40	sil	1.54	7.6	4	13.2	16
10–30	AB	10YR 3/2		13.0	27.0	0.50	sil/sicl	1.46	7.0	3	6.6	23
30–44	Bt	10YR 3/3	D F V 10YR 3/2	12.5	27.2	0.39	sil/sicl	1.45	7.9	3	4.6	27
44–68	Btk1	10YR 4/3	D F V 10YR 4/2	12.1	25.8	0.24	sil	1.34	8.3	3	4.0	68
68–90	Btk2	10YR 5/4	P F V 10YR 3/2	16.9	20.4	0.17	sil	1.22	8.7	4	2.5	85
90–138	Btk3	10YR 6/4	P F V 10YR 4/2	18.4	16.1	0.16	sil	1.20	8.7	5	0.5	99
138–169	Bk	10YR 6/4		18.7	17.5	0.13	sil	1.20	8.7	5	1.4	104
169–200+	Bk	10YR 6/4		19.9	16.1	0.14	sil	1.20	8.7	6	0.8	84

† The matrix colors given are moist Munsell colors of broken ped faces.
‡ Continuity: C = continuous, D = discontinuous, P = patchy; distinctness: F = faint, D = distinct; location: A = all faces of peds, V = vertical faces of peds; color: moist Munsell color; not present in every horizon.
§ Ratio of fine clay to total clay.
¶ Oven-dry bulk density.
# 1:1 H_2O pH.
†† Exchangeable sodium percentage.
‡‡ Soil organic carbon.
§§ Calcium carbonate equivalent.

for $m_1, m_2, \ldots, m_n$ were obtained from the product of the bulk density (g cm^{-3}) and the total clay content (g g^{-1}) for each horizon. For SOC distributions, the values for $m_1, m_2, \ldots, m_n$ were obtained from the product of the bulk density and the SOC content (g g^{-1}) for each horizon. Evaluation of Eq. [2] yields the total mass of clay per unit area, M_{z_n}, within the depth interval $0 \leq z \leq z_n$.

The center of mass, d_z (cm), for clay or SOC distributed between the soil surface and depth z can be obtained from

$$d_z = \frac{\int_0^z s\ m(s)ds}{\int_0^z m(s)ds} \qquad [3]$$

which is the usual expression for computing center of mass. This expression was evaluated by using the alternative form

$$d_{z_n} = \frac{1}{2}\left[\frac{m_1(z_1^2) + m_2(z_2^2 - z_1^2) + \ldots + m_n(z_n^2 - z_{n-1}^2)}{m_1(z_1) + m_2(z_2 - z_1) + \ldots m_n(z_n - z_{n-1})}\right] \qquad [4]$$

which yields the center of mass, d_{z_n}, for clay or SOC distributed within the depth interval $0 \leq z \leq z_n$.

RESULTS AND DISCUSSION

Abbreviated field descriptions and laboratory data for four representative pedons are presented in Table 1. Descriptions and laboratory data for the other 16 pedons are available in Ricks (2002).

Effect of Irrigation on Soil Chemical Properties

Mollic colors were described to similar depths in both the irrigated and dryland pedons (Table 1), and there were no significant differences in the amount of SOC (g cm^{-2}) in the upper 30 cm of the pedons (M_{30}) between dryland and irrigated pedons at either site location (Table 2).

The pH of the surface horizon (Ap) of both the irrigated Keith and Richfield profiles was significantly higher ($P = 0.01$) than the dryland profiles by nearly one unit (Table 2). The only significant differences in pH occurred in the surface horizons. However, ESP was

Table 2. Mean values for selected properties. For each soil series, results were averaged for five irrigated and five dryland pedons.

Characteristic†	Mean dryland	Mean irrigated
Richfield pedons		
Total clay, %, Ap	32.3	30.2
Total clay, %, Bt1	32.9	35.1
Total clay, %, Bt2	36.5	40.4*
Total clay, %, Btk1	31.7	36.2***
FC:TC† Ap	0.40	0.36
FC:TC Bt1	0.36	0.52***
FC:TC Bt2	0.53	0.61**
FC:TC Btk1	0.42	0.44
Total clay M_{50}, g cm^{-2}	2511.4	2779.4**
Total clay d_{50}, cm	26.6	28.3***
Total clay M_{102}, g cm^{-2}	5224.4	5646.7*
Total clay d_{102}, cm	55.6	57.6
1:1 H_2O pH, Ap	6.5	7.4***
Depth to carbonates, cm	83.0	64.8**
Thickness of mollic colors, cm	96.4	80.8
SOC M_{30}, g cm^{-2}	32.4	33.8
Keith pedons		
Total clay, %, Ap1	19.1	19.7
Total clay, %, Ap2	24.7	26.2*
Total clay, %, Bw (dry), Bt (irr)	23.4	26.2***
Total clay, %, Btk1	22.8	24.3*
FC:TC Ap1	0.38	0.39
FC:TC Ap2	0.42	0.46*
FC:TC Bw (dry), Bt (irr)	0.34	0.36
FC:TC Btk1	0.26	0.24
Total clay M_{48}, g cm^{-2}	1481.6	1735.1***
Total clay d_{48}, cm	24.9	24.8
1:1 H_2O pH, Ap1	6.2	7.3***
Depth to carbonates, cm	56.8	54.8
Thickness of mollic colors, cm	44.7	41.1
SOC M_{30}, g cm^{-2}	38.1	38.7

* Indicates significant differences between dryland and irrigated pedons at the 0.10 probability level.
** Indicates significant differences between dryland and irrigated pedons at the 0.05 probability level.
*** Indicates significant differences between dryland and irrigated pedons at the 0.01 probability level.
† FC:TC, ratio of fine clay to total clay; d_z, center of mass (cm) of clay or SOC distributed between soil surface and depth z (cm); M_z, total mass of clay or SOC per unit area (g cm^{-2}) between soil surface and depth z (cm).

elevated throughout the profile in the irrigated pedons (Table 1). The quality of the irrigation water (Table 3) is the likely cause for the observed changes in these soil chemical properties. The irrigation water samples for both sites have a low sodium hazard and a medium salinity hazard, although conductivity values < 0.075 S m^{-1} are acceptable for most crops (U.S. Salinity Laboratory Staff, 1954). Although the EC and SAR values of the irrigation water are not predicted to present salinity or sodicity hazards for row crop production, it is evident that Na^+ levels have increased in the soils with 30 yr of irrigation. Salt accumulation can occur through irrigation of crops with water that is only slightly saline, around 0.07 S m^{-1} (Buol et al., 1997).

At the Keith and Richfield sites, the landowners apply enough irrigation water during each growing season to nearly double the natural amount of annual precipitation, and have been doing so for the past 28 to 31 yr (Ricks, 2002). The equations of Arkley (1963) and Jenny (1941) both predict an increase in the depth at which secondary carbonates are encountered with increased precipitation, or in this study, irrigation. However, the effect of irrigation on pedogenic calcium carbonate in the present study is rather complex. The mean depth to carbonates was reduced significantly ($P = 0.05$) in the irrigated Richfield pedons. However, in the Keith pedons, there was no difference in the depth to pedogenic $CaCO_3$ with respect to irrigation (Table 2). The models of Arkley (1963) and Jenny (1941) both predict that carbonates will accumulate at the maximum depth of leaching. Thus, the irrigation practices employed at the study site locations may not actually change the depth reached by the wetting front. Deep percolation is considered a waste of the water resource as well as the dissolved nutrients and/or agrochemicals leached below the rooting depth by the irrigation water. However, Stone et al. (1994) has reported significant amounts of drainage from both the Richfield and Keith soils. It is possible that very little deep percolation of water has occurred in these soils, thus the depth to secondary carbonates was not greatly affected, even though the natural amount of precipitation was doubled.

Another possible explanation for the general lack of differences with respect to $CaCO_3$ between dryland and irrigated pedons is the chemistry of the irrigation water. Conditions were likely unfavorable for the dissolution and translocation of carbonates because of the high Ca^{2+} content and pH of the irrigation water (Table 3). In summary, the chemistry of the irrigation water applied is likely different than natural rainfall, although the chemistry of natural precipitation was not analyzed in this study. Therefore, at the Keith and Richfield sites, the system may favor the precipitation of $CaCO_3$.

Effects of Irrigation on Particle Size Distribution

Even if increasing precipitation via irrigation does not necessarily correspond to a deeper depth of wetting, the upper part of the irrigated soil profile must surely be wetter for a longer period of time relative to dryland conditions. This could lead to increased mineral weathering in addition to a greater number of shrink-swell cycles. Also, more water can carry greater loads of suspended solids in solution. Thus, irrigation can affect the particle size distribution, namely the clay content, by increasing clay movement within the soil profile, and by possibly increasing mineral weathering to produce a greater quantity of layer silicates.

Table 3. Chemical data for irrigation water sampled in 2000 from the wells used to irrigate the Richfield and Keith site locations in Finney and Thomas County, Kansas, respectively.

Location	pH	Ca	Mg	K	Na	EC†	SAR‡	Salinity hazard	Sodium hazard
		µg mL^{-1}				S m^{-1}			
Richfield	7.3	86.6	25.8	6.0	32.7	0.07	0.8	medium	low
Keith	7.7	37.4	17.4	7.1	41.4	0.05	1.4	medium	low

† EC, electrical conductivity.
‡ Sodium adsorption ratio.

In the field, there were noticeable differences in the morphology between irrigated and dryland pedons. Clay coatings were generally more strongly expressed and extensive in the irrigated pedons. At the Keith site, clay films began at a depth of 30 cm under irrigation vs. 43 cm in the dryland, and this affected the horizon nomenclature (Table 1). For example, in the irrigated Keith pedon, clay films were described in the third horizon, which extended from 30 to 44 cm, and were described as discontinuous, faint, very dark grayish brown (moist color 10YR 3/2) located on the vertical faces of peds. Since clay films were observed, and there was a perceptible increase in clay content, the horizon was designated Bt. In contrast, no clay films were observed at a nearly equal depth (27–43 cm) in the dryland pedon. Therefore, this horizon was named Bw. Since the maximum total clay content in the Keith pedons occurred in the Ap2 horizon of the dryland pedon and the AB horizon of the irrigated pedon, this indicates that either cultivation brought argillic horizon material to the surface, and/or that the soil surface was eroded.

In the Richfield pedons, clay films were first encountered at the same depth (21–23 cm) but were described to deeper depths in the irrigated profiles vs. the dryland profiles, affecting the horizon nomenclature of the deepest horizons described (Table 1). For example, clay coatings were described to 114 cm in the dryland Richfield pedon, and to 180 cm in the irrigated Richfield pedon. Also, clay coatings were continuous in the Bt1 and Bt2 horizons of the irrigated pedon but discontinuous at the equivalent depth in the dryland pedon.

Confirming the macroscopic observations of clay coatings in the field, a greater abundance of oriented or birefringent clay and plasma separations were also generally observed in thin sections obtained from irrigated vs. dryland horizons for both the Keith and Richfield soils. In some horizons, these differences affected the plasmic fabric and b-fabric nomenclature (Table 4). These micromorphological differences were observed in selected horizons of the dryland and irrigated Keith pedons. Skelsepic plasmic fabric was described in the dryland Ap2 (11–27 cm) and Bw horizons (27–43 cm). In contrast, ma-skelsepic fabric was described in the irrigated AB (10–30 cm) and Bt (30–44 cm) horizons (Table 4). By the micromorphological nomenclature of Stoops (2003), the dryland Ap2 and Bw horizons and the irrigated AB and Bt horizons all have granostriated b-fabrics. Similarly, the dryland Btk1 horizon (43–59 cm) was described with ma-skelsepic plasmic fabric, as opposed to a skel-masepic fabric, which has more matrix plasma separations, in the irrigated Btk1 horizon (44–68 cm).

Parallel micromorphological observations were also made in the Richfield pedons, although irrigation tended to affect the plasmic and b-fabric nomenclature more than in the Keith pedons (Table 1). The Bt2 horizon (35–53 cm) in the irrigated Richfield pedon contains more plasma separations in the matrix as compared with the Bt2 horizon (38–57 cm) of the dryland pedon (Fig. 3). The irrigated Bt2 horizon was described as having skel-masepic plasmic fabric (or more parallel striated b-fabric), whereas the dryland Bt2 horizon was described with ma-skelsepic plasmic fabric (or more granostriated b-fabric).

Table 4. Abbreviated micromorphology of selected horizons.

Depth	Horizon	Plasmic fabric†	Predominant b-fabric‡
cm			
	Dryland Richfield pedon S00KS055011		
13–21	Ap2	ma-skelsepic	granostriated
21–38	Bt1	ma-skelsepic	granostriated
38–57	Bt2	ma-skelsepic	granostriated
57–83	Btk1	ma-skelsepic	granostriated
83–114	Btk2	ma-skelsepic	granostriated
114–163	Bk1	skelsepic	granostriated
	Irrigated Richfield pedon S00KS055016		
0–12	Ap1	§	§
12–23	Ap2	ma-skelsepic	granostriated
23–35	Bt1	ma-skelsepic	granostriated
35–53	Bt2	skel-masepic	parallel striated
53–72	Btk1	skel-masepic	parallel striated
72–99	Btk2	ma-skelsepic	granostriated
99–122	Btk3	skel-masepic	parallel striated
122–145	Btk3	skel-masepic	parallel striated
	Dryland Keith pedon S00KS193001		
11–27	Ap2	skelsepic	granostriated
27–43	Bw	skelsepic	granostriated
43–59	Btk1	skel-masepic	parallel striated
59–71	Btk2	ma-skelsepic	granostriated
71–104	Btk2	ma-skelsepic	granostriated
150–175	Bk	skelsepic	granostriated
175–200+	Bk	skelsepic	granostriated
	Irrigated Keith pedon S00KS193006		
10–30	AB	ma-skelsepic	granostriated
30–44	Bt	ma-skelsepic	granostriated
44–68	Btk1	skel-masepic	parallel striated
68–90	Btk2	ma-skelsepic	granostriated
90–138	Btk3	ma-skelsepic	granostriated

† Terminology of Brewer (1976).
‡ Terminology of Stoops (2003).
§ No thin sections prepared.

At both sites, micromorphological investigations revealed a higher proportion of oriented or birefringent clay in the matrix of irrigated A and B horizons. However, the differences in the micromorphological nomenclature are subtle and perhaps insignificant; masepic and skelsepic plasmic fabrics are both considered to orient clay through stress from shrinking and swelling (Brewer, 1976; Dalrymple and Jim, 1984; Jim, 1990). The same is true for granostriated and parallel striated b-fabrics (Stoops, 2003). The presence of these stress-induced fabrics prohibits the conclusion that a greater amount of plasma in the irrigated horizons resulted from illuviation. For argillic Richfield horizons, coefficient of linear extensibility (COLE) values range from 0.05 to 0.08 (Fraser, 1990). These COLE values are considered high enough to prevent the identification of illuvial clay in thin section (Nettleton et al., 1969).

The total clay contents of selected Richfield and Keith pedons (Fig. 4) show that that the irrigated pedons have more pronounced clay maxima. In *t* test comparisons of the five irrigated and five dryland Richfield pedons, two horizons contained significantly different clay contents (Table 2). These were the Bt2 horizon ($P = 0.10$) and the Btk1 horizon ($P = 0.01$). When the results were averaged across the five irrigated and five dryland Keith pedons, the mean total clay content of the irrigated Ap2, Bw or Bt, and Btk1 horizons (core designations) had

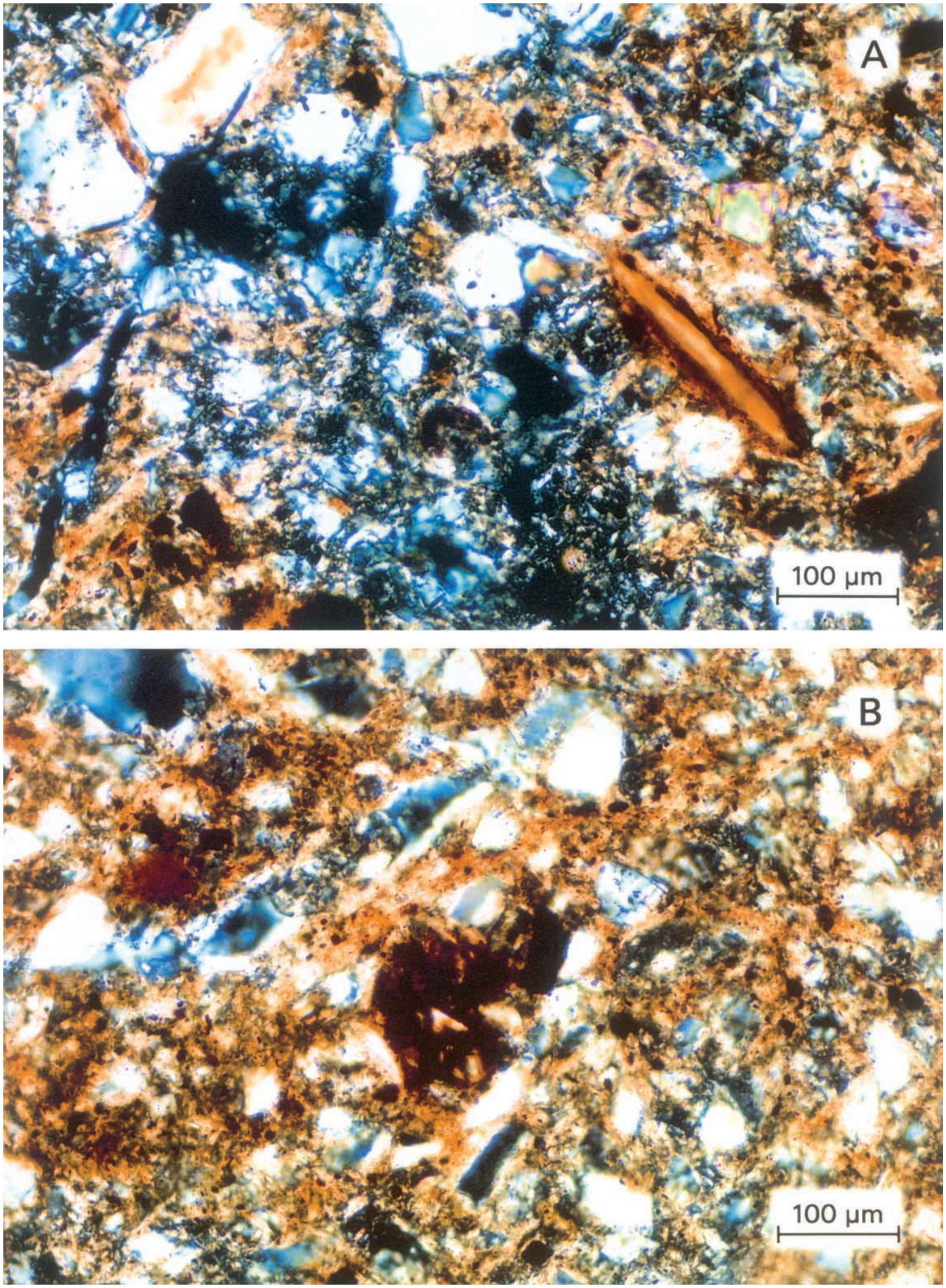

Fig. 3. Thin section micrographs. (A) Richfield dryland Bt2 (38–57 cm). Plasmic fabric is ma-skelsepic, or granostriated. This micrograph shows a biotite grain weathering, a process which releases 2:1 clays. (B) Richfield irrigated Bt2 (35–53 cm). Plasmic fabric is skel-masepic (or parallel striated), with a larger proportion of oriented clay in the matrix as well as coating skeleton grains. Cross-polarized light, long-axis frame length = 665 μm.

significantly higher clay contents than dryland horizons at equivalent depths (Table 2).

Fine clay (<0.2 μm in diam.) is considered to be the most mobile particle size fraction. The ratio of fine clay to total clay (FC:TC) is one indicator of clay movement within the soil profile. A horizon that has a higher ratio than horizons above probably has become enriched with fine clay through illuviation. The same is true when comparing horizons that occur at nearly equivalent depths in irrigated and dryland soils.

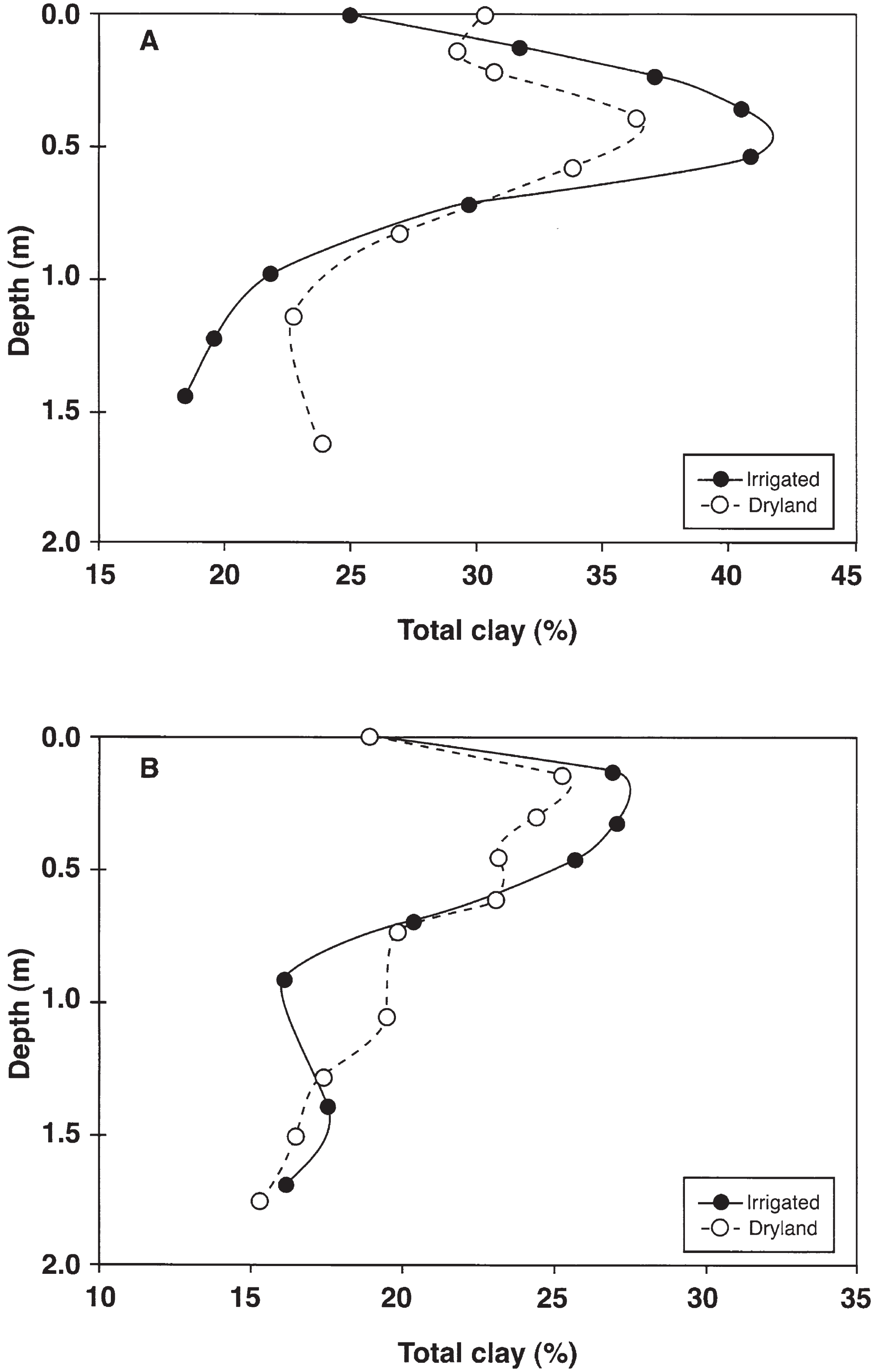

Fig. 4. Total clay vs. depth for (A) Richfield dryland (S00KS055011) and irrigated (S00KS055016), and (B) Keith dryland (S00KS193001) and irrigated (S00KS193006).

There were no differences in the means of the surface horizon FC:TC ratio of irrigated and dryland Keith and Richfield pedons; however, there were some differences in lower horizons (Table 2). The Bt1 of the irrigated Richfield pedons had a significantly higher ($P = 0.01$) FC:TC ratio than the Bt1 of the dryland pedons. The Bt2 horizons of irrigated pedons also had greater FC:TC than the dryland site ($P = 0.05$). In the Keith pedons, the second horizon (designated Ap2 in the cores) had significantly higher ($P = 0.10$) mean FC:TC values in the irrigated and dryland profiles, respectively. This may also indicate the incorporation of Bt material into the Ap2 horizon via tillage.

Effects of Irrigation on the Whole Pedon Clay Content and Distribution

If higher clay contents and FC:TC ratios in certain horizons were caused only by illuviation of clay within the soil profile, then lower total clay contents and FC:TC ratios would be expected in the upper or eluvial horizons of these pedons. This is not indicated by the laboratory data (Table 2), as the irrigated Richfield Ap and Bt1 horizon had mean total clay contents and FC:TC ratios that were not significantly different from the values measured in the dryland Ap and Bt1 horizon. The same is true for the Keith pedons. No significant differences in the total clay content and FC:TC ratio were observed in the Ap1 horizon, but the Keith Ap2 horizon of the irrigated pedons contained significantly greater total clay and FC:TC ratios.

One possible explanation for this disparity is that the addition of irrigation water increased the weathering of primary minerals such as biotite (Fig. 3), and led to increased production of layer silicates in irrigated pedons. Comparing data on a horizon-by-horizon basis is relatively simple, but forming interpretations from these results can be quite difficult. Therefore, an attempt was made to try to quantify these differences or changes in the distribution of clay throughout the soil profile.

All 10 Richfield pedons had complete particle size distribution data to a depth of 102 cm. Mean values for M_{102} were significantly greater ($P = 0.10$) in the irrigated pedons with values of 5224.4 and 5646.7 g cm^{-2} for the dryland and irrigated pedons, respectively (Table 2). When only the low-carbonate portion of the pedons (upper 50 cm) is considered, the mean values for M_{50} were significantly greater ($P = 0.05$) in the irrigated pedons, with values of 2511.4 and 2779.4 g cm^{-2} for the dryland and irrigated pedons, respectively (Table 2). For the Keith pedons, the mean values for M_{48} were also significantly higher ($P = 0.01$) under irrigation, with values of 1481.6 and 1735.1 g cm^{-2}, for dryland and irrigated pedons, respectively.

When the first moment or center of mass of the clay content distribution, d_z, is calculated for Richfield pedons from 0 to 102 cm, the mean depth for d_{102} in the dryland pedons is 55.6 cm vs. 57.6 cm for the irrigated pedons and was not significantly different. There does, however, seem to be a difference in the center of mass when only the upper 50 cm of the pedons is considered. There was a significant increase in d_{50} ($P = 0.01$) in the irrigated pedons, with d_{50} occurring at mean depths of 26.6 vs. 28.3 cm below the soil surface in the dryland and irrigated pedons, respectively. Recall that the upper 50 cm of both the irrigated and dryland Richfield pedons have relatively low $CaCO_3$ content and that this region contains the upper, more strongly expressed portion of the argillic or illuvial horizon. As indicated by the mean depth to secondary carbonates (Table 2), the average modern depth of leaching extends to 83.0 and 64.8 cm in the dryland and irrigated pedons, respectively. Therefore, clay is able to disperse and is free to move in at least the upper 50 cm of the solum, and moves to increasingly deeper depths with increased precipitation via irrigation. For the Keith pedons, mean values of d_{48} were not significantly different, occurring at 24.9 and 24.8 cm in the dryland and irrigated pedons, respectively (Table 2).

The total amount of clay (M_z) in the relatively low pedogenic carbonate portion of the profile was higher under irrigation at both the Keith and Richfield sites. This parameter indicates that at both locations there may have been more production of silicate clay; that is, more mineral weathering with irrigation when compared with the dryland pedons. The center of mass of the clay distribution (d_z) occurred deeper in the soil profile under irrigation at the Richfield site, but was not different at the Keith site. The lower position of d_z at the Richfield site indicates that there has also been more movement and redistribution of clay with irrigation. If the irrigated surface horizons had significantly lower clay contents than the dryland surface horizons, an increase in clay movement alone might explain these differences. However, the surface horizon clay contents of irrigated and dryland pedons were not different at either site location.

The data suggest that irrigation is causing more than a simple redistribution of the clay within the soil profile. At the Richfield site, the increase in clay content and the accentuated argillic horizon morphology are likely products of both increased clay movement and accelerated mineral weathering relative to the natural dryland conditions. Figure 3 shows a biotite grain weathering, a process which releases 2:1 clays (Bisdom et al., 1982; Fanning et al., 1989). Since similar positions for d_z indicate that clay illuviation has not increased with irrigation at the Keith site, one possible explanation for the increased mass of clay within irrigated profiles may therefore be derived from increased mineral weathering following ≈30 yr of irrigation.

Aside from irrigation, other cultural practices and their effects may have impacted these same properties. Irrigated soils receive greater rates of nitrogen fertilizer (nearly exclusively in anhydrous ammonia form) than less-productive dryland soils. It is possible that the combined effect of increased soil acidity from fertilization as well as increased precipitation from irrigation interacted to create conditions for more intense mineral weathering. Wind erosion is a problem for the nearly level, semiarid soils of western Kansas, and both dryland and irrigated land is subject to losses of topsoil via wind erosion (Mech and Woodruff, 1967). It is difficult to determine if the dryland sites would be significantly more susceptible to wind erosion. Both the irrigated and dryland parts of the field would both be subject to wind erosion at different times of the year, depending on the crop that is grown. However, irrigation may reduce soil losses due to wind erosion. The soil erodibility index (I) of the wind erosion equation may be adjusted to a less-erodible condition (lower *I* value) under irrigation (USDA-NRCS, 2002). In the present study, there was no evidence that the dryland sites were more eroded than the irrigated sites.

Sodium added in the irrigation water (Table 3) at both sites may exacerbate the effect of increased precipitation on clay movement by dispersing the clay and making it more mobile. Perhaps mineral weathering also increases through physical processes. Irrigation increases the number of wetting and drying cycles in the soil profile. Therefore, physical mineral weathering may increase with increased shrinking and swelling, as proposed in a similar comparison of irrigated and dryland soils in Morroco by Mathieu (1978). Stress features were observed in thin section, and COLE values are sufficiently high to predict shrinking and swelling in Richfield and Keith argillic horizons (Fraser, 1990; Nettleton et al., 1969).

CONCLUSIONS

Mineral weathering and argillic horizon formation are conventionally viewed as relatively slow processes, which vary with the type of parent material and climatic conditions. Birkeland (1999) and Buol et al. (1997) indicate that these processes generally occur on the order of thousands of years. In sharp contrast, observations made in this study indicate that 28 to 31 yr of irrigation in western Kansas may have significantly increased the rates at which these processes occur relative to natural conditions. At the Richfield site location, laboratory and micromorphological data suggest that the movement and redistribution of clay, as well as the production of layer silicates, has increased in the upper portion of the soil profile under irrigated farming system practices. The higher values for M_z suggest that more clay was produced, that is, more mineral weathering has occurred, with irrigation when compared with the dryland pedons. The irrigated Keith pedons also contained a greater amount of total clay (as well as oriented or birefringent clay in thin section) than the dryland Keith pedons, an increase that is not necessarily of illuvial origin. No changes were observed in the calcium carbonate content and distribution or in the organic C content of irrigated Richfield and Keith soils. The irrigation water chemistry is the likely explanation for the lack of changes in the depth to calcium carbonate and the calcium carbonate content of these two soils.

ACKNOWLEDGMENTS

The authors would like to thank Phil Studer and Andrew Larson Jr. for allowing this work to be conducted on their property and for sharing information regarding their farming practices. We thank several USDA-NRCS soil scientists who helped locate and sample the sites, and the Soil Survey Laboratory of the National Soil Survey Center for characterizing some of the pedons in this study.

REFERENCES

Arkley, R.J. 1963. Calculation of carbonate and water movement in soil from climatic data. Soil Sci. 96:239–248.

Birkeland, P.W. 1999. Soils and geomorphology. 3rd ed. Oxford University Press, New York.

Bisdom, E.B.A., G. Stoops, J. Delvigne, P. Curmi, and J.-J. Altemueller. 1982. Micromorphology of weathering biotite and its secondary products. Pedologie 32:225–252.

Bordovsky, D.G., M. Choudhary, and C.J. Gerard. 1999. Effect of tillage, cropping, and residue management on soil properties in the Texas rolling plains. Soil Sci. 164:331–340.

Brewer, R. 1976. Fabric and mineral analysis of soils. Robert E. Krieger Publ. Co., Huntington, NY.

Buchanan, R., and R. Buddemeier. 2001. The High Plains Aquifer. Pub. Inf. Circ. 18. Kansas Geological Survey, Lawrence, KS.

Buol, S.W., F.D. Hole, R.J. McCracken, and R.J. Southard. 1997. Soil genesis and classification. 4th ed. Iowa State Univ. Press, Ames, IA.

Dalrymple, J.B., and C.Y. Jim. 1984. Experimental study of soil microfabrics induced by isotropic stresses of wetting and drying. Geoderma 34:43–68.

Dixon, R.M. 1960. The effects of irrigation on the chemical properties of some north central and southwestern Kansas soils. M.S. thesis. Kansas State Univ., Manhattan.

Fanning, D.S., V.Z. Keramidas, and M.A. El-Desoky. 1989. Micas. p. 551–634. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. 2nd ed. Book Ser. No. 1. SSSA, Madison, WI.

Fraser, S.H. 1990. Genesis and classification of loess-derived soils of western Kansas. MS thesis. Kansas State Univ., Manhattan.

Goodin, D.G., J.E. Mitchell, M.C. Knapp, and R.E. Bivens. 1995. Climate and weather atlas of Kansas: An introduction. Educational Ser. 12. Kansas Geological Survey, Lawrence, KS.

Gunal, H. 2001. Clay illuviation and calcium carbonate accumulation along a precipitation gradient in Kansas. Ph.D. diss. Kansas State Univ., Manhattan.

Heakal, M.S., and M.H. Al-Awajy. 1989. Long-term effects of irrigation and date palm production on torripsamments, Saudi Arabia. Geoderma 44:261–273.

Hesse, P.R. 1971. Piper Method. Textbook for soil chemical analysis. Chemical Publ. Co., New York.

Hussein, J., M.A. Adey, and H.A. Elwell. 1992. Irrigation and dryland cultivation effects on the surface properties and erodibility of a Zimabwe vertisol. Soil Use Manage. 8:96–103.

Jenny, H. 1941. Factors of soil formation: A system of quantitative pedology. McGraw-Hill, New York.

Jenny, H., and C.D. Leonard. 1933. Functional relationships between soil properties and rainfall. Soil Sci. 38:363–381.

Jim, C.Y. 1990. Stress, shear deformation and micromorphological clay orientation: A synthesis of various concepts. Catena 17:431–447.

Khalifa, E.M., M. Reda, and M.H. Al-Awajy. 1989. Changes in soil fabric of torripsamments under irrigated date palms, Saudi Arabia. Geoderma 44:307–317.

Kilmer, V.J., and L.T. Alexander. 1949. Methods of making chemical analyses of soils. Soil Sci. 68:15–24.

Lueking, M.A., and J.S. Schepers. 1985. Changes in soil carbon and nitrogen due to irrigation development in Nebraska's Sandhills soils. Soil Sci. Soc. Am. J. 49:626–630.

Lynn, W.C. 1958. The effect of irrigation on the chemical properties of some Kearny County soils. M.S. thesis. Kansas State Univ., Manhattan.

Mathieu, C. 1978. Influence de l'irrigation sur l'evolution de quelques caracteres fondamentaux des sols argileux des plaines du Maroc oriental. Aspects micromorphologiques. Sci. Sol 2:95–112.

Mech, S.J., and N.P. Woodruff. 1967. Wind erosion on irrigated lands. p. 964–973. *In* R.M. Hagan et al. (ed.) Irrigation of agricultural lands. Agron. Monogr. 11. ASA, Madison, WI.

Naddih, B.I. 1960. The effect of known quality irrigation water on the chemical properties of soils of western Kansas. M.S. thesis. Kansas State Univ., Manhattan.

Nettleton, W.D., K.W. Flach, and B.R. Brasher. 1969. Argillic horizons without clay skins. Soil Sci. Soc. Am. Proc. 33:121–125.

Ricks, D.K. 2002. Effects of thirty years of irrigation on the properties of semi-arid soils in Kansas. M.S. thesis. Kansas State Univ., Manhattan.

SAS Institute. 1999. SAS/STAT user's guide. Release 8.01. SAS Inst., Cary, NC.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 1998. Field book for describing and sampling soils. Version 1.1. National Soil Survey Center, USDA-NRCS, Lincoln, NE.

Soil Survey Laboratory Staff. 1996. Soil survey laboratory methods manual. Soil Survey Investigation Rep. No. 42. v. 3.0. National Soil Survey Center, Lincoln, NE.

Stone, L.R., A.J. Schlegel, F.R. Lamm, and W.E. Spurgeon. 1994. Storage efficiency of preplant irrigation. J. Soil Water Conserv. 49(1):72–76.

Stoops, G. 2003. Guidelines for analysis and description of soil and regolith thin sections. SSSA, Madison, WI.

Tabatabai, M.A., and J.M. Bremner. 1970. Use of the Leco automatic 70-second carbon analysis of soils. Soil Sci. Soc. Am. Proc. 34: 608–610.

USDA-NRCS. 2002. National Agronomy Manual [Online]. Available at: http://www.nrcs.usda.gov/technical/agronomy.html [verified 1 July 2004]. USDA-NRCS, Washington, DC.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Dep. of Agric. Handbook 60 [Online]. Available at: http://www.ussl.ars.usda.gov/hb60/hb60.htm [verified 1 July 2004]. USDA-ARS, George E. Brown, Jr. Salinity Lab, Riverside, CA.

Wierzchos, J., M.T. Garcia-Gonzales, and J. Boixadera. 1997. Structure and structure-related characteristics of dryland and long-term irrigated Xerochrept soils. Arid Soil Res. Rehabil. 11:127–138.

Williams, M.A. 2001. Influence of water on the carbon and nitrogen dynamics of annually-burned tallgrass prairie. Ph.D. diss. Kansas State Univ., Manhattan.